

Express Mail EU943994198US

**APPLICATION
FOR
UNITED STATES LETTERS PATENT**

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TITLE: HIGH Q FACTOR INTEGRATED CIRCUIT
INDUCTOR

DOCKET NO.: END920030116US1

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HIGH Q FACTOR INTEGRATED CIRCUIT INDUCTOR

FIELD OF THE INVENTION

The present invention relates to the field of integrated circuits; more specifically, it relates to high quality (Q) factor inductor structures, methods of fabricating high Q factor inductor structures and methods of integration of high Q factor inductor structures into integrated circuit manufacturing processes.

BACKGROUND OF THE INVENTION

Inductors are used in many integrated circuits intended for radio-frequency (RF) applications. Inductors are typically fabricated of relatively thick metals on or near the surface of integrated circuit chips. As the RF frequency that integrated circuits operate at increases, power consumption increases unless the Q factor of the inductors increase as well. The Q factor of an inductor is defined as $Q = E_s / E_l$, where E_s is the amount energy that is stored in the reactive portion of the inductor and E_l is the amount of energy that is lost in the reactive portion of the inductor. The Q value of an inductor can also be expressed as $Q = W_0 L / R$, where W_0 is the resonant frequency, L is the inductive value and R is the resistance of the inductor. The significance of the second equation is that Q increases as R decreases.

Fabricating the inductor using high conductivity metal, wide metal lines or thick metal lines can reduce resistance in an inductor. However, the use of wide metal lines inductors can consume large amounts of integrated circuit chip surface and suitable areas

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of an integrated circuit for placement of inductors is often very limited. The fabrication of thick metal inductors especially when using high conductivity metals and the subsequent integration of high conductivity, thick metal inductors into the inter-connection layers of integrated circuits is problematical. Therefore, there is a need for
5 high Q factor, thick metal inductors formed of high conductivity metal and methods and integration schemes compatible with inter-connection layer fabrication techniques for forming inductors for integrated circuit chips.

SUMMARY OF THE INVENTION

10 A first aspect of the present invention is a method of forming an inductor, comprising in the order recited: (a) providing a semiconductor substrate; (b) forming a dielectric layer on a top surface of the substrate; (c) forming a lower trench in the dielectric layer; (d) forming a resist layer on a top surface of the dielectric layer; (e) forming an upper trench in the resist layer, the upper trench aligned to the lower trench, a
15 bottom of the upper trench open to the lower trench; and (f) completely filling the lower trench and at least partially filling the upper trench with a conductor in order to form the inductor.

A second aspect of the present invention is a method of forming an inductor, comprising in the order recited: (a) providing a semiconductor substrate; (b) forming a
20 dielectric layer on a top surface of the substrate; (c) forming a lower trench in the dielectric layer; (d) forming a conformal conductive liner in the lower trench and over a

top surface of the dielectric layer; (e) forming a conformal Cu seed layer over the
conductive liner; (f) forming a resist layer on the substrate; (g) forming an upper trench in
the resist layer, the upper trench aligned to the lower trench, a bottom of the upper trench
open to the lower trench; (h) electroplating Cu to completely fill the lower trench and at
5 least partially fill the upper trench in order to form the inductor; (i) removing the resist
layer; (j) selectively forming a conductive passivation layer over all exposed Cu surfaces;
and (k) selectively removing the Cu seed layer from regions of the conductive liner
overlying the surface of the dielectric layer and removing the conductive liner from the
surface of the dielectric layer.

10 A third aspect of the present invention is a semiconductor structure, comprising:
an inductor having a top surface, a bottom surface and sidewalls, a lower portion of the
inductor extending a fixed distance into a dielectric layer formed on a semiconductor
substrate and an upper portion extending above the dielectric layer; and means to
electrically contact the inductor.

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BRIEF DESCRIPTION OF DRAWINGS

The features of the invention are set forth in the appended claims. The invention
itself, however, will be best understood by reference to the following detailed description
of an illustrative embodiment when read in conjunction with the accompanying drawings,
20 wherein:

FIG. 1 is a top view of an inductor and contact pad according to a first embodiment of the present invention;

FIG. 2 is a top view of an inductor and contact pad according to a second embodiment of the present invention;

5 FIG. 3 is a top view of an inductor and contact pad according to a third embodiment of the present invention;

FIGs. 4A through 4F are partial cross-sectional views illustrating fabrication steps common to the first, second and third embodiments of the present invention;

FIGs. 5A through 5F are partial cross-sectional views illustrating fabrication steps
10 subsequent to the steps illustrated in FIGs. 4A through 4F, common to the first and second embodiments of the present invention;

FIG. 5G is a partial cross-sectional view illustrating a fabrication step subsequent to the steps illustrated in FIGs. 5A through 5F, for the second embodiment of the present invention; and

15 FIGs. 6A through 6G are partial cross-sectional views illustrating fabrication steps subsequent to the steps illustrated in FIGs. 4A through 4F, for the third embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

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FIG. 1 is a top view of an inductor and contact pad according to a first embodiment of the present invention. In FIG. 1, an integrated circuit chip **100A** includes an inductor **105** having integral vias **110A** and **110B** for interconnection to wiring levels (not shown) within the integrated circuit chip. While inductor **105** is illustrated as a spiral inductor the invention is applicable to inductors of other shapes as well. Integrated circuit chip **100A** also includes an I/O terminal pad **115** in the bottom of a via **120** for interconnection to wiring levels (not shown) within the integrated circuit chip and a conductive passivation layer **125** formed on top of I/O terminal pad **115** and overlapping via **120**.

FIG. 2 is a top view of an inductor and contact pad according to a second embodiment of the present invention. In FIG. 2, an integrated circuit chip **100B** includes inductor **105** having integral vias **110A** and **110B** for interconnection to wiring levels (not shown) within the integrated circuit chip. While inductor **105** is illustrated as a spiral inductor the invention is applicable to inductors of other shapes as well.

Integrated circuit chip **100B** also includes I/O terminal pad **115** in the bottom of via **120** for interconnection to wiring levels (not shown) within the integrated circuit chip, conductive passivation layer **125** formed on top of I/O terminal pad **115** and overlapping via **120**, a pad limiting metallurgy (PLM) layer **130** and a solder ball **135** formed over conductive passivation layer **125**. Solder balls are also known as controlled collapse chip connection (C4) balls, C4 solder balls and solder bumps. For the purposes of the present invention the term solder ball may be replaced with the term solder column. Solder

columns are cylinders of Pb or Pb/Sn alloy and the present invention is applicable to solder column interconnect technology as well.

FIG. 3 is a top view of an inductor and contact pad according to a third embodiment of the present invention. In FIG. 3, an integrated circuit chip **100C** includes inductor **105** having integral vias **110A** and **110B** for interconnection to wiring levels (not shown) within the integrated circuit chip. While inductor **105** is illustrated as a spiral inductor the invention is applicable to inductors of other shapes as well. Integrated circuit chip **100C** also includes I/O terminal pad **115** in the bottom of via **120** for interconnection to wiring levels (not shown) within the integrated circuit chip, a conductive passivation coated raised pad **140** formed on top and overlapping via **120**, PLM layer **130** and solder ball **135** formed over conductive passivation layer **125**. PLM layer **130** is fully landed on raised pad **140**.

FIGs. 4A through 4F are partial cross-sectional views illustrating fabrication steps common to the first, second and third embodiments of the present invention. FIGs. 4A through 4F may be taken through line S1-S1 of FIG. 1, line S2-S2 of FIG. 2 or of line S3-S3 of FIG. 3.

In FIG. 4A a semiconductor substrate **200** includes I/O terminal pad **115** and underpass wires **205A** and **205B**. A top surface **210** of I/O terminal pad **115** and top surfaces **215A** and **215B** of underpass wires **205A** and **205B** respectively, are co-planer with a top surface **220** of substrate **200**. Underpass wires **205A** and **205B** and I/O terminal pad **115** electrically connect with wires in other wiring levels (not shown) and

eventually electrically connect to active devices within substrate **200**. Underpass wires **205A** and **205B** provide electrical connection to inductor **105** (see FIGs. 1, 2 or 3). In one example, I/O terminal pad **115** and underpass wires **205A** and **205B** comprise a TaN/Ta liner (the TaN layer is formed first) and a Cu core and are formed by a damascene or a dual damascene process; and the portion of substrate **200** illustrated in FIG. 4A comprises SiO₂. The TaN/Ta liner may be eliminated or replaced with a liner of comprised of other materials such as W, Ti and TiN.

In a damascene process, a trench is etched in a dielectric layer, an optimal conductive conformal liner and conductive seed layer deposited on the bottom and sidewalls of the trench as well as the top surface of the dielectric layer. Then a core conductor is deposited or plated onto the seed layer, filling the trench. Finally a chemical-mechanical-polish step is performed, removing all liner, seed layer and core conductor from the top surface of the dielectric layer and leaving a conductive filled trench, a top surface of the trench co-planer with the top surface of the dielectric layer. In a dual damascene process, vias open to a lower wiring level are formed in the bottom of the trench prior to formation of the liner or core conductor.

In FIG. 4B, a first dielectric layer **225** is formed on top surface **220** of substrate **200** as well as on top surfaces **215A** and **125B** and **210** of underpass wires **205A** and **205B** and I/O terminal pad **115** respectively. A second dielectric layer **230** is formed on a top surface **235** of first dielectric layer **225**. A third dielectric layer **240** is formed on a top surface **245** of second dielectric layer **230**. In one example, first dielectric layer **225**

is Si_3N_4 about 350 Å to 1050 Å thick, second dielectric layer **230** is SiO_2 about 1500 Å to 5000 Å thick and third dielectric layer **240** is Si_3N_4 about 2000 Å to 6000 Å thick.

It is possible to practice the present invention using only a single dielectric layer of for example, either SiO_2 or Si_3N_4 or a dual layer of for example, SiO_2 over Si_3N_4 in
5 place of the three dielectric layers **225**, **230** and **240**.

In FIG. 4C, portions of third dielectric layer **240** aligned over underpass wires **205A** and **205B** and I/O terminal pad **115** are removed, exposing top surface **245** of second dielectric layer **230**. In FIG. 4D, portions of second dielectric layer **230** and first dielectric layer **225** aligned over underpass wires **205A** and **205B** and I/O terminal pad
10 **115** are removed forming trenches **250A** and **250B** and via 120 respectively and exposing top surfaces **215A**, **215B** and **210** of underpass wires **205A** and **205B** and I/O terminal pad **115** respectively. Additionally, portions of third dielectric layer **240** and portions of second dielectric layer **230** are removed down to a depth D1 forms trenches **260**.

It should be understood that trenches **250A**, **250B** and **260** are in reality one
15 interconnected spiral trench in which inductor **105** (see FIGs. 1, 2 and 3) will be formed and that trenches **250A** and **250B** indicate those portions of the spiral trench in which vias **110A** and **110B** (see FIGs. 1, 2 and 3) are formed. Trenches **250A**, **250B** and **260** only appear as separate trenches in cross-section and to avoid confusion as to which portion of the spiral trench is being described at a given moment, the “separate” trench terminology
20 will be used.

The exact removal depth D1, of second dielectric layer **230** in trenches **260** is not critical as long as sufficient second dielectric layer **230** remains in trenches **260** to protect dielectric layer **225** when dielectric layer **225** is removed in trenches **250A** and **250B** and via 120. In one example, D1 is about 2500 Å to 7500 Å. D2 is the depth of trenches **260** and D3 is the depth of trenches **250A** and **250B** and via 120. The difference in depth between trenches **260** and trenches **250A** and **250B** and via 120 is D3-D2.

The steps illustrated in FIGs. 4C and 4D can be accomplished by several methods. In a first method, a first layer of photoresist is applied, a first photolithographic process performed, a first reactive ion etch (RIE) process selective to etch, in the example presented *supra*, Si₃N₄ over SiO₂ is performed to define trenches **250A** and **250B** and via 120 in third dielectric layer **240** as illustrated in FIG. 4C. Then the first resist layer is removed, a second resist layer is applied, a second photolithographic process followed by a second RIE process selective to etch, in the example presented *supra*, SiO₂ over Si₃N₄ is performed in order to fully open trenches **250A** and **250B** and via 120 in second and third dielectric layer **240** as well as etch D1 into second dielectric layer **230** in trenches **260** as illustrated in FIG. 4D. The second layer of resist is then removed.

In a second method, a single dual tone resist layer (stacked or composite positive/negative resist) is applied, and a photolithographic step using a dual tone photomask is performed to completely remove the resist layer where trenches **250A** and **250B** and via 120 are to be formed and only partially remove the resist layer (thin the resist layer down) where trenches **260** are to be formed. A single RIE etch is then

performed to form the structures illustrated in FIG. 4D (FIG. 4C is skipped). The dual tone resist layer is then removed. In either case a clean up etch may be performed, for example a wet etch using dilute HF.

5 In FIG. 4E, a conformal liner **265** is deposited on a top surface **270** of third dielectric layer **240** as well as on the sidewalls and bottoms of trenches **250A**, **250B** and **260** and via **120**. A conformal seed layer **275** is then deposited on a top surface **280** of liner **265**. In one example, liner **265** is about 200 Å to 5000 Å of Ta deposited over about 10 Å to 1000 Å of TaN and seed layer **275** is about 100 Å to 1500 Å of Cu, both formed by physical vapor deposition (PVD) or ionized physical vapor deposition (IPVD).

10 In FIG. 4F, a CMP process is performed to remove seed layer **275** from liner **265** wherever liner **265** is contacting top surface **270** of third dielectric layer **265**, but leave the seed layer on the sidewalls and bottom of trenches **250A**, **250B** and **260** and via **120**. CMP may be followed by an optional clean up etch. In the example of seed layer **275** being Cu, a dilute oxalic acid/HF etchant may be used for the clean up etch. An optional
15 Cu clean up etch may also be performed.

In a second method, the aforementioned CMP process is not performed, and seed layer **275** remains everywhere on top of liner **265**. Seed layer **275** will be removed in subsequent steps as described *infra*.

This concludes the part of the inductor fabrication that is common to all
20 embodiments of the present invention. It should be noted that while the invention has been described using first dielectric layer **225**, second dielectric **230** and third dielectric

layer **240**, it is possible to practice the present invention using more or fewer dielectric layers. For example, a single dielectric layer or two dielectric layers may be used instead of the three dielectric layers described *supra*.

FIGs. 5A through 5F are partial cross-sectional views illustrating fabrication steps
5 subsequent to the steps illustrated in FIGs. 4A through 4F, common to the first and second embodiments of the present invention. FIGs. 5A through 5F are taken through line S1-S1 of FIG. 1 in the case of the first embodiment or line S2-S2 of FIG. 2 in the case of the second embodiment.

In FIG. 5A, a resist layer **285** is formed and patterned, exposing seed layer **275** on
10 the bottom and sidewalls of trenches **250A**, **250B** and **260**, but protecting via **120**. Resist layer **285** has thickness D4. Patterned resist layer **285** serves to increase the depth of trenches **250A**, **250B** and **260**. In one example, D4 is about 8 to 20 microns thick. In one example, resist layer **285** may be any conventional spun applied resist. In a second example D4 is about 20 to 50 microns. Above about 20 microns, Riston®, manufactured
15 by Dupont (Wilmington, De.) or other roll applied resists may be used. The value of D4 is one of the factors controlling the thickness of inductor **105** (see FIG. 2) that will be formed as illustrated in FIG. 5B and described *infra*.

In FIG. 5B trenches **250A**, **250B**, and **260** are partially filled with a thickness D5
of metal by electroplating using seed layer **275** as a cathode to form inductor **105**. The
20 thickness D5 is another factor controlling the thickness of inductor **105**. Note that individual islands of seed layer **275** are electrically connected by liner **265** which is

effectively a blanket, albeit conformal, conductive coating extending over all of substrate 200. Generally, the plating process is stopped when the metal reaches within about 1 to 2 microns of filling trench 260 of resist layer 285 in order make subsequent removal of the resist layer easier. It is possible to overfill the trenches and then CMP the excess metal.

- 5 In one example, inductor 105 is formed of electroplated Cu. An exemplary Cu plating process is described in United States Patent 6,368,484 to Volant et al., which is hereby incorporated in its entirety by reference. In one example D5 is about 5 to 50 microns.

In FIG. 5C, resist layer 285 (see FIG. 5B) is removed. The width W1 and spacing S1 of the coils of inductor 105 is not limited by the present invention. W1 and S1 are
10 limited by the minimum line/space printable with the particular photolithographic process (resist system, mask technology and exposure tool and wavelength) at the lower end and by the amount of integrated real estate available for inductors at the upper end. In one example W1 is about 2 to 30 microns and S1 is about 2 to 20 microns.

In the second method, seed layer 275 is now removed from regions where it is
15 exposed, for example by wet etch. In one example, the wet etch is a mixture of sulfuric acid, ammonium persulfate and water. The etch rate for Cu must be slow enough that a controllable removal of seed layer 275 may be accomplished without substantial etching or undercutting of inductor 105 or other plated Cu structures.

In FIG. 5D, a first conductive passivation layer 290 is selectively electroplated
20 over all exposed surfaces of seed layer 275 but not on exposed liner 265. A second conductive passivation layer 295 is selectively electroplated over all exposed surfaces of

first conductive passivation layer 290 but not on exposed liner 265. In one example, first conductive passivation layer 290 is Ni about 2000 Å to 6000 Å thick and second conductive passivation layer 295 is Au about 1200 Å to 4000 Å thick. It is possible to use a single conductive passivation layer. First conductive passivation layer 290 and
5 second conductive passivation layer 295 are equivalent to conductive passivation layer 125 illustrated in FIGs. 1, 2 and 3 and described *supra*.

In FIG. 5E, all exposed liner 265 is removed. In the example of liner 265 being TaN/Ta and second conductive passivation layer 295 being Au, a fluorine based RIE may be used.

10 In FIG. 5F, a blanket organic passivation layer 300 is applied and photo-lithographically patterned to expose a contact pad 305 over I/O terminal pad 115. In one example blanket organic passivation layer 300 is polyimide. A polyimide layer is typically provided by coating with a polyimide precursor and then converting the precursor to the cured polyimide by heating. Commercially available polyimide
15 precursors (polyamic acid) or various polyimide precursors manufactured by DuPont, (Wilmington, De.) are available under the trade designations Pyralin. These polyimide precursors come in many grades including those available under the trade designations PI-2555, PI2545, PI-2560, PI-5878, PIH-61454 and PI-2540. Some of these are pyromellitic dianhydride-oxydianline (PMA-ODA) polyimide precursors. The cured
20 polyimide layer is about 0.4 to 5 microns thick. Contact pad 305 may be used as a

wirebond pad. In wire bonding, an Al or Au wire is ultrasonically welded or bonded to a contact pad. This concludes fabrication of the first embodiment of the present invention.

FIG. 5G is a partial cross-sectional view illustrating a fabrication step subsequent to the steps illustrated in FIGs. 5A through 5F, for the second embodiment of the present invention. FIG. 5G is taken through line S2-S2 of FIG. 2. In FIG. 5G, PLM layer 130 is formed to electrically contact raised contact pad 305 and solder ball 135 is formed on PLM layer 130. PLM 130 and solder ball 135 may be formed by a through mask plated C4 process. Through mask plated C4 processes are well known in the art, but briefly involve evaporating or sputtering a PLM and a seed layer, forming a patterned photomask on a wafer, plating Pb or Pb/Sn alloy, stripping the photomask and etching away exposed PLM and seed layer. An exemplary C4 plating process is described in United States Patent 6,297,140 to Uzoh et al. and in United States Patent 6,251,428 also to Uzoh et al., both of which are hereby incorporated in their entireties by reference. In one example of a through plated C4 process, PLM layer 130 comprises a triple layer of TiW/CrCu/Cu and solder ball 135 is comprised of Pb or Pb/Sn alloy. Solder ball 135 is illustrated after either a post-evaporative or post plating reflow anneal. In one example, the TiW layer is about 250 Å to 2000 Å thick, the CrCu layer is about 100 Å to 2000 Å thick and the Cu layer is about 1000 Å to 20,000 Å thick. This concludes fabrication of the second embodiment of the present invention.

Because inductor 105 (see FIG. 5G) is significantly higher than contact pad 305, an evaporative C4 processes cannot be used to form PLM 130 and solder ball 135 of FIG.

5G because the molybdenum mask used in an evaporative C4 process would be so far from the contact pad so as to cause intolerable amount of under mask evaporation. The third embodiment of the present invention provides a pad structure that allows for the use of an evaporative C4 process.

5 FIGs. 6A through 6G are partial cross-sectional views illustrating fabrication steps subsequent to the steps illustrated in FIGs. 4A through 4F, for the third embodiment of the present invention. FIGs. 6A through 6G are taken through line S3-S3 of FIG. 3.

 In FIG. 6A, resist layer **285** is formed and patterned, exposing seed layer **275** on the bottom and sidewalls of trenches **250A**, **250B** and **260** and via **120**. The composition
10 and thickness of resist layer **285** has been described *supra*.

 In FIG. 6B trenches **250A**, **250B** and **260** and via **120** are partially filled with a metal by electroplating using seed layer **275** as a cathode to form inductor **105** and raised pad **140**. Note that individual islands of seed layer **275** are electrically connected by liner **265** which is effectively a blanket, albeit conformal, conductive coating extending over
15 all of substrate **200**. Generally, the plating process is stopped when the metal reaches about 1 to 2 microns of the top surface of resist layer **285** in order make subsequent removal of the resist layer easier. It is possible to overfill the trenches and then CMP the excess metal. The composition and thickness of inductor **105** has been described *supra*.

 In FIG. 6C, resist layer **285** (see FIG. 6B) is removed. The width W1 and spacing
20 S1 of the coils of inductor **105** have been discussed *supra*.

In the second method, seed layer **275** is now removed from regions where it is exposed as described *supra*.

In FIG. 6D, first conductive passivation layer **290** is selectively electroplated over all exposed surfaces of inductor **105** and raised pad **140** but not on exposed liner **265**.

- 5 Second conductive passivation layer **295** is selectively electroplated over all exposed surfaces of first conductive passivation layer **290** but not on exposed liner **265**. The compositions and thicknesses of first passivation **290** and second passivation layer **295** have been described *supra*.

- In FIG. 6E, all exposed liner **265** is removed. In the example of liner **265** being
10 TaN/Ta and second conductive passivation layer **295** being Au, a fluorine based RIE may be used.

- In FIG. 6F, blanket organic passivation layer **300** is applied and photo-
lithographically patterned to expose a raised contact pad **310** over I/O terminal pad **115**.
The composition of blanket organic passivation layer **300** has been described *supra*. At
15 this point in the fabrication of the third embodiment of the present invention, fabrication could be altered, a polyimide or other passivating coating applied as described *supra* and raised contact pad **310** used as a wirebond pad or as a landing pad for a cantilevered beam connection such as tape automated bonding (TAB) packaging in a fourth embodiment of the present invention.

- 20 Continuing with the third embodiment of the present invention, in FIG. 6G, PLM layer **130** is formed on raised contact pad **310** and solder ball **135** is formed on PLM layer

130. PLM 130 and solder ball 135 may be formed by either a through mask plated C4 or an evaporative C4 process. Because of the height of raised contact pad 310 it is now possible to use an evaporative C4 process since the molybdenum evaporation mask will close enough to raised contact pad 310 to avoid the problems described *supra* when the mask is too far from the pad. Evaporative C4 processes are well known in the art, but involve placing a molybdenum mask in close proximity to a semiconductor wafer, first evaporating or sputtering PLM through holes in the mask, then evaporating Pb or Pb/Sn alloy through the same holes and then removing the mask. In one example of an evaporative C4 process, PLM layer 130 comprises a triple layer of Cr/CrCu/Au and solder ball 135 is comprised of Pb or Pb/Sn alloy. In one example, the Cr layer is about 100 Å to 1000 Å thick, the Cu layer is about 100 Å to 2000 Å thick and the Au layer is about 100 Å to 1,000 Å thick. Through mask plated C4 processes and materials have been described *supra*. This concludes fabrication of the third embodiment of the present invention.

15 All of the embodiments of the present invention have been shown to produce inductors having Q factors about equal or greater than 40 and having inductances of about equal or greater than 0.5 nH.

Thus, the present invention provides not only high Q factor, thick metal inductor formed of a high conductivity metal but also a method and integration for forming the inductor compatible with inter-connection layer fabrication techniques of integrated circuit chips.

The description of the embodiments of the present invention is given above for the understanding of the present invention. It will be understood that the invention is not limited to the particular embodiments described herein, but is capable of various modifications, rearrangements and substitutions as will now become apparent to those skilled in the art without departing from the scope of the invention. For example, while the present invention is described forming the inductor from a liner of TaN/Ta, a seed layer of Cu, and a Cu core, other conductive materials may be substituted. Therefore it is intended that the following claims cover all such modifications and changes as fall within the true spirit and scope of the invention.

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